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No local cancellation between directionally opposed first-order and second-order motion signals

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Abstract

Despite strong converging evidence that there are separate mechanisms for the processing of first-order and second-order motion, the issue remains controversial. Qian, Andersen and Adelson (J. Neurosci., 14 (1994), 7357–7366) have shown that first-order motion signals cancel if locally balanced. Here we show that this is also the case for second-order motion signals, but not for a mixture of first-order and second-order motion even when the visibility of the two types of stimulus is equated. Our motion sequence consisted of a dynamic binary noise carrier divided into horizontal strips of equal height, each of which was spatially modulated in either contrast or luminance by a 1.0 c/deg sinusoid. The modulation moved leftward or rightward (3.75 Hz) in alternate strips. The single-interval task was to identify the direction of motion of the central strip. Three conditions were tested: all second-order strips, all first-order strips, and spatially alternated first-order and second-order strips. In the first condition, a threshold strip height for the second-order strips was obtained at a contrast modulation depth of 100%. In the second condition, this height was used for the first-order strips, and a threshold was obtained in terms of luminance contrast. These two previously-obtained threshold values were used to equate visibility of the first-order and second-order components in the third condition. Direction identification, instead of being at threshold, was near-perfect for all observers. We argue that the first two conditions demonstrate local cancellation of motion signals, whereas in the third condition this does not occur. We attribute this non-cancellation to separate processing of first-order and second-order motion inputs.

Keywords: Motion; Motion detection; Human vision; Contrast modulation; Second-order motion

1. Introduction

Recent work has demonstrated that moving images can contain at least two sorts of spatio-temporal structure, labelled as first-order and second-order, and this fact has led to the idea that the human visual system may utilise different mechanisms for the analysis of the two sorts of information (Derrington & Badcock, 1985; Chubb & Sperling, 1988; Cavanagh & Mather, 1989; Lu & Sperling, 1995). Moving first-order structure is captured by a description of the way that image intensity varies across space-time; moving second-order structure describes the way that some other local property of the image, such as local contrast or local element size, varies across space-time (Chubb & Sperling, 1988). This paper is concerned with the question of whether the early processing of first-order and second-order motion input is indeed carried out by separate mechanisms.

Psychophysical (e.g. Ledgeway & Smith, 1994; Edwards & Badcock, 1995; Smith & Ledgeway, 1997, 1998; Scott-Samuel & Georgeson, 1999), physiological (e.g. Zhou & Baker, 1993), functional imaging (e.g. Smith, Greenlee, Singh, Falk, & Hennig, 1998) and neuropsychological (e.g. Greenlee & Smith, 1997; Vaina, Makris, Kennedy, & Cowey, 1998) evidence all suggest the existence of separate mechanisms for the processing of first-order and second-order motion input. Several models of human detection of visual motion have been suggested which assume just such a separability (e.g. Wilson, Ferrera, & Yo, 1992; Lu &

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Sperling, 1995), but the issue remains controversial (e.g. Johnston, McOwan & Buxton, 1992; Grzywacz, Watamaniuk, & McKee, 1995; Taub, Victor, & Conte, 1997; Del Viva & Morrone, 1998).

One possible means of testing whether or not first-order and second-order motion inputs are processed separately at an early stage is suggested by an experiment published by Qian, Andersen, and Adelson (1994): they demonstrated that in a stimulus consisting of oppositely drifting luminance-defined dots, it possible to abolish the perception of transparency by locally balancing the motion signals. This finding was interpreted in terms of spatial-frequency-selective local inhibition of motion signals in different directions within the motion pathways; in other words, if any two oppositely-drifting dots fall into the same receptive field, the net result is no motion signal, as the signals within the mechanism are equal and opposite. The same observation holds true for two identical drifting sinusoidal gratings, moving in opposite directions: these result in a counterphasing pattern, with no perception of transparency. Thus if two oppositely moving inputs are processed by the same mechanism, local cancellation should result in no net motion signal within the visual system; conversely, if the two motion inputs are not processed by the same mechanism, then both directions of motion will be seen transparently.

An initial attempt to assess cancellation of first- and second-order motion using similar methods to those employed by Qian et al. (1994) failed because of the presence of a density cue in our version of their stimulus sequences. In order to allow the presentation of second-order as well as first-order dots, it was necessary to add two constraints to the Qian et al. (1994) stimulus: firstly, the dots could not overlap at any point; secondly, the dots were larger than in Qian et al.'s (1994) experiment. The former constraint avoided the problem of introducing first-order information into a second-order dot if the two overlapped; the latter was necessary to produce salient second-order dots. In Qian et al.'s (1994) original experiments, observers performed a 2AFC task between a standard stimulus containing 50% locally balanced and 50% non-balanced dots, and comparison stimuli with varying ratios of the two types of dot. The criterion used was one of transparency, and the psychometric function produced showed that comparison stimuli with more than 50% locally balanced dots appeared less transparent than the standard stimulus, and those with less than 50% locally balanced dots appeared more transparent. In our version of this stimulus, however, pilot observations revealed that observers were able to use the local density within the stimulus as a criterion: if the stimulus appeared more dense locally, then it contained more locally balanced dots, and vice versa. When instructed to make judgements based on this cue, observers generated data which were identical to those collected when they were instructed to use transparency as the only criterion, suggesting that they may have made use of the density cue in transparency judgements and/or vice versa. We assume that the presence of the density cue was due to the two additional constraints imposed in our motion sequences.

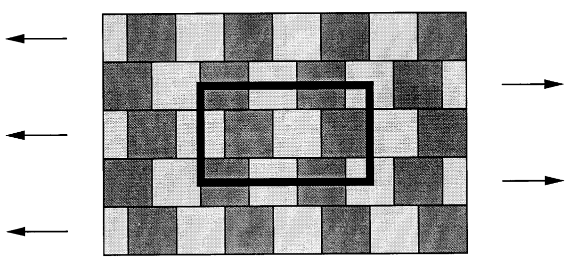

Fig. 1. Diagrammatic representation of the stimulus used and the experimental logic. Horizontally drifting vertical sinusoidal modulations of a carrier are stacked, alternate layers moving, in opposite directions. In the case of a luminance-defined modulation, the light and dark squares represent areas of high and low luminance; for a contrast-defined grating, they show areas of high and low contrast. The solid black rectangle represents a spatially uniform receptive field. As shown it would not register any directional motion signal, as the movement across it is equal and opposite, summing to zero. An increase in the height of the component strips of the motion stimulus would result in a signal, as then the balance between leftwards and rightwards motion would be destroyed.

An alternative approach to measuring local cancellation was employed by Georgeson and Scott-Samuel (2000). Their stimulus consisted of a stack of strips of vertically-oriented, drifting sinusoidal grating, with alternate strips moving to the left and right (see Fig. 1); the strip height was systematically reduced until the direction of motion of the central strip could no longer be reported. The logic of the experiment assumed that at this point local cancellation of the two opposite motion signals was occurring within a receptive field, yielding no net motion signal.

Because of the presence of the density cue in our stimuli based on Qian et al.'s (1994) design, we instead used motion sequences similar to those employed by Georgeson and Scott-Samuel (2000) in the experiments presented below.

Here we: (i) confirm that first-order local motion signals cancel, as has previously been demonstrated (Qian et al., 1994; Georgeson & Scott-Samuel, 2000); (ii) show that the same is true of contrast-modulated (second-order) motion signals; and (iii) demonstrate that no such cancellation occurs when the two types of input are combined in a mixed motion stimulus. We attribute this non-cancellation to separate early processing of first-order and second-order motion inputs.

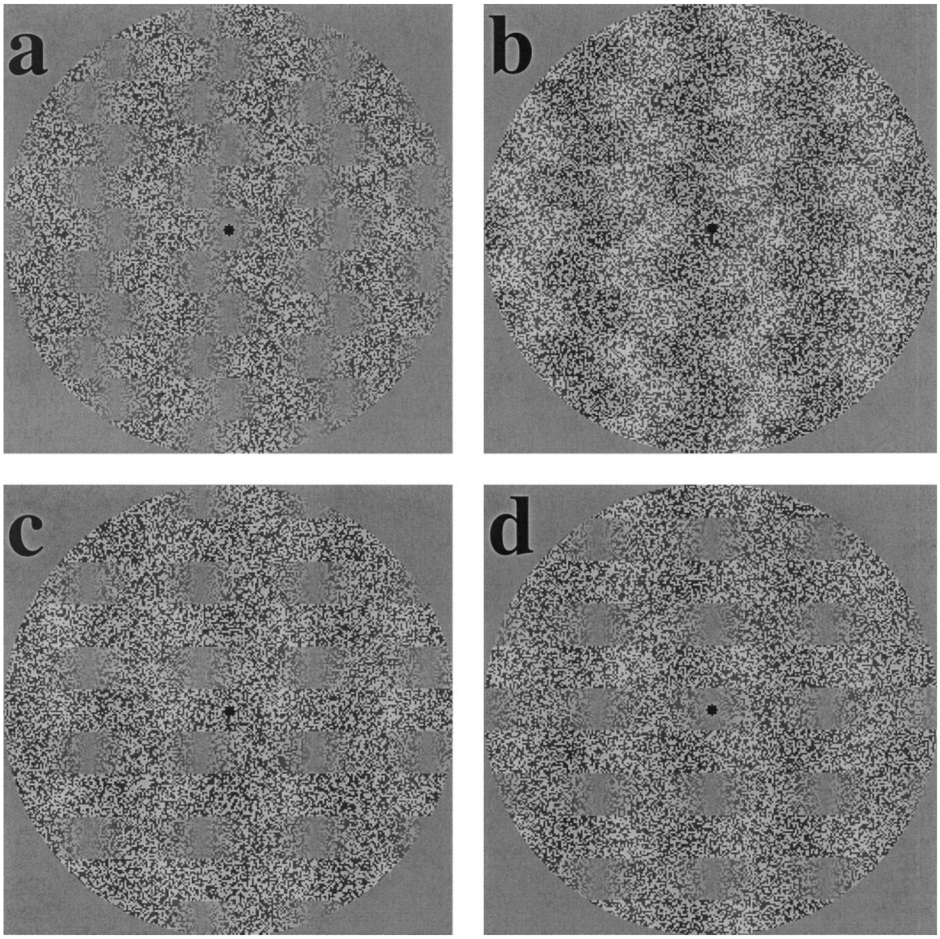

Fig. 2. One frame from each of the motion sequences used is shown: (a) second-order, contrast-modulated strips; (b) first-order, luminance-modulated strips; (c) spatially alternating first-order and second-order strips, with a first-order strip in the middle of the display: (d) spatially alternating first-order and second-order strips, with a second-order strip in the middle of the display. Spatially alternate strips moved in opposite directions (to the left or right). Note that these images are not gamma-corrected, as was the case for the experimental display.

2. Methods

The stimuli were generated by an Apple Macintosh 7500 computer and displayed on a gamma-corrected Apple 1705 monitor with a frame refresh rate of 75 Hz and a mean luminance of 38.5 cd/m^2. The motion sequences were constructed from a circular patch of dynamic 2-D binary noise carrier with a Michelson contrast of 50%. The carrier was divided into horizontal strips of equal height, and each strip was horizontally sinusoidally modulated in either contrast or luminance, dependent upon which of the three conditions was being tested. The modulation was drifted in 90° phase steps; each step coincided with the refreshing of the dynamic noise carrier. The update rate was 15 Hz, resulting in a modulation drift rate of 3.75 Hz. This combination of drift rate and carrier contrast was chosen to avoid the presence of first-order artefacts in the second-order strips of the stimulus (Scott-Samuel & Georgeson, 1999); a dynamic 2-D noise carrier was chosen for the same reason (Smith & Ledgeway, 1997). The spatial frequency of the modulation was 1.0 c/deg. The diameter of the patch was 4° at the viewing distance of 1.22 m, and the noise element size was 1×1 minarc. One cycle of motion was shown on each 266 ms trial. A central fixation spot was provided; one strip was always centred on this spot and the task of the observers was to indicate the direction of motion of this central strip in a single-interval, binary choice task with no feedback. Three observers were used: one of the authors and two naïve observers. Fig. 2 illustrates the images used in each of the three experiments.

Three experiments were performed. The purpose of the first two was to establish the strip height and contrasts required to construct the stimulus for Experiment 3.

2.1. Experiment 1

All the strips in the stimulus were contrast modulated (Fig. 2a), and the modulation depth was set at 100%. All strips were the same height, and this height was varied across trials using the method of constant stimuli; each observer responded to 48 trials at each of seven strip heights chosen on the basis of a pilot experiment. The threshold height for correct identification of the direction of motion of the central strip was determined by fitting a Weibull function to each observer's data and measuring the strip height corresponding to 75% correct performance.

2.2. Experiment 2

The strip height was fixed at the threshold value obtained in Experiment 1 for each observer. The strips were now first-order (Fig. 2b), and the amplitude of the luminance contrast was varied across trials to obtain a 75% performance threshold figure. Thus Experiments 1 and 2 yielded stimuli of equal strength by equating the visibility (in terms of direction discrimination) for each observer of both the contrast-modulated and the luminance-modulated dynamic noise at a particular strip height.

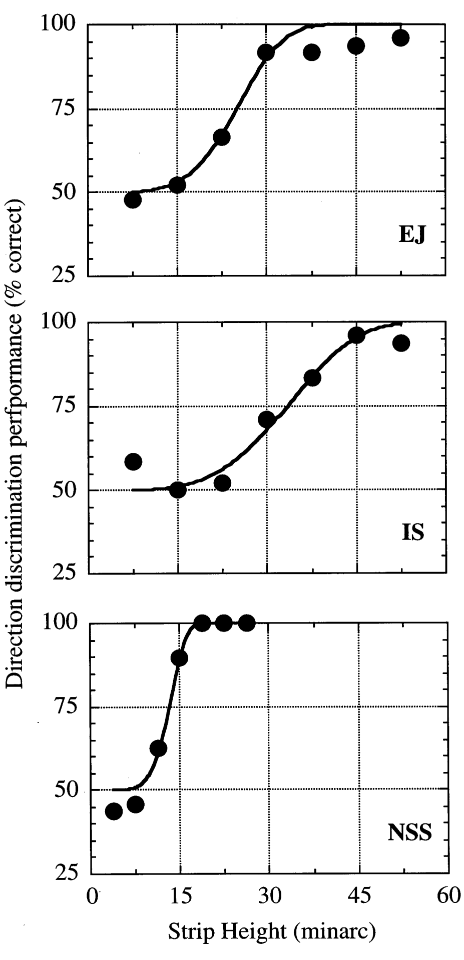

Fig. 3. Psychometric functions relating direction discrimination performance (percent correct) to strip height in an experiment in which all strips contained second-order motion and had a modulation depth of 100% (Experiment 1). Results for three observers are shown separately.

2.3. Experiment 3

The equally visible components established in Experiments 1 and 2 were combined to give a composite stimulus consisting of spatially alternating first-order and second-order strips. The strip height for both first-order and second-order motion was that determined in Experiment 1 and used in Experiment 2. The contrast modulation depth of the second-order stimulus was 100%. The contrast of the first-order stimulus was the threshold value determined in Experiment 2 for each observer. The result was a composite stimulus with both elements at threshold (when viewed embedded in strips of the same type). The central strip (the one to be judged) was either first-order (Fig. 2c) or second-order (Fig. 2d), determined randomly with equal probability on each trial. In order to ensure that any slight inaccuracy in the measurement of the luminance contrast threshold determined in Experiment 2 did not affect the results, the experiment was repeated several times using a range of first-order luminance contrast levels, centred on the threshold value.

3. Results

3.1. Experiment 1

The results of Experiment 1 are shown in Fig. 3. Performance on the direction discrimination task declined with decreasing strip height for all observers. The threshold strip heights (at 75% correct direction discrimination performance) were 25.1 minarc for EJ, 33.4 minarc for IS, and 13.2 minarc for NSS. The rather lower threshold value for NSS is probably explained by practice effects; this observer has had considerably more exposure to the second-order stimuli used here than the other two naïve observers. These threshold values indicate the strip height at which local cancellation of the oppositely-drifting contrast modulations occurred.

3.2. Experiment 2

The results from Experiment 2 are shown in Fig. 4 as squares and dashed lines. Performance on the direction discrimination task declined with decreasing luminance contrast for all observers. The threshold luminance contrasts (at 75% correct direction discrimination performance) were 3.4% for EJ, 2.2% for IS, and 3.7% for NSS. These threshold values are shown by the vertical, solid-shafted arrows on each graph, and indicate the luminance contrast at which local cancellation of the oppositely-drifting luminance modulations occurred for a strip height equal to the threshold value for second-order strips measured for each observer in Experiment

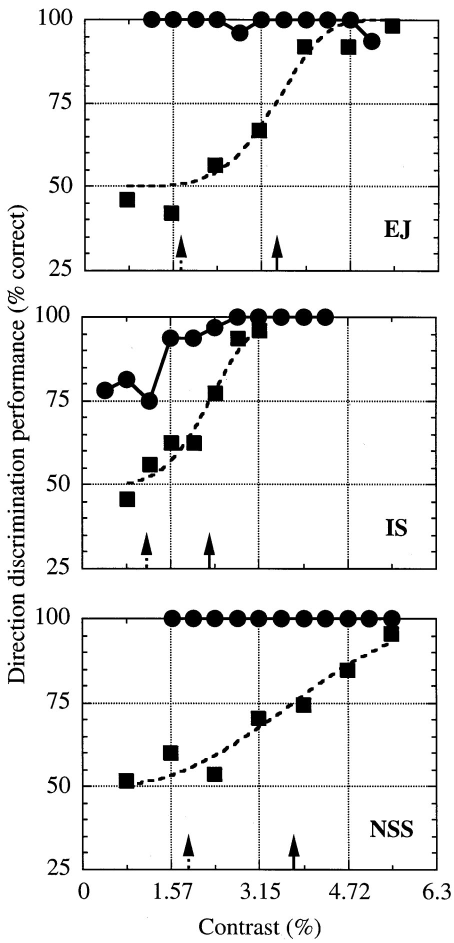

Fig. 4. Squares and dashed lines show direction discrimination performance (percent correct) in Experiment 2 plotted against contrast for three observers: all strips contained first-order motion and the strip height was fixed at the cancellation threshold measured for second-order motion in Experiment 1. Circles and solid lines show direction discrimination performance (percent correct) in Experiment 3 plotted against the luminance of the first-order strips (percent contrast), for three observers: spatially alternate strips contained first-order or second-order motion. The second order strips were always at 100% modulation depth and the strip height was fixed at the threshold measured in Experiment 1. The vertical solid-shafted arrow on each graph shows the location of the luminance contrast threshold measured in Experiment 2; the vertical arrow with a dashed shaft indicates half this threshold value.

1. Note that the variability in the threshold figures obtained here can, in part, be attributed to the fact that the strip height used varied across observers.

3.3. Experiment 3

The results from Experiment 3 are shown in Fig. 4 as circles and solid lines. At the point marked by the solid-shafted, vertical arrow (the luminance contrast threshold measured in Experiment 2), direction discrimination performance is at or near to 100% correct for all observers. If it were the case that the first-order and second-order inputs were processed by the same low-level mechanism, then performance should have been at threshold levels at this point of equal visibility of the first-order and second-order strips. Performance remained near-perfect for other luminance contrast values around the point of equal visibility for each observer. For two observers (NSS and EJ), this was true even when the first-order component had a contrast of half the threshold value (the contrast needed for cancellation by first-order motion). At this contrast level, performance was at chance in the first-order-only condition (see Fig. 4, vertical arrow with dashed shaft). For the third observer (IS), performance remained close to perfect only for contrasts down to 1.57%, at which point performance in the first-order-only condition was about 60%. Although this observer's performance tails off at low contrasts, suggesting motion cancellation, it is likely that this simply reflects the greater proximity to absolute detection threshold for this observer, whose cancellation threshold was low.

Informal observation demonstrated that the near-perfect direction discrimination performance at the point of equal visibility was maintained at lower strip heights; i.e. it was still possible to discriminate the direction of the central strip in conditions that were not only at, but also well below, the threshold levels measured in Experiments 1 and 2. Performance only failed when the strips were too short to be resolved, and it proved impossible to judge which was the central one. It was, however, still possible to identify the direction of motion of the first-order and second-order components, as the stimulus appeared transparent and the two types of motion could be distinguished. Thus cancellation between first-order and second-order motion did not occur, even when the strip height was reduced to levels well below the threshold for stimuli containing strips which were all of the same type.

4. Discussion

We have demonstrated that in displays containing either all first-order or all second-order locally balanced motion signals, cancellation occurs. This is not, however, the case for a mixture of the two types of stimulus. The explanation for the cancellation of locally balanced motion signals of the same type is that both fall within the same receptive field, and therefore the net signal from that receptive field is zero (Qian et al., 1994; Georgeson & Scott-Samuel, 2000). The lack of cancellation between first- and second-order stimuli revealed here therefore suggests that the two types of motion signal are not initially processed by the same mechanism. This, in turn, suggests that there are at least two distinct pathways for motion processing, one dealing with moving modulations of contrast (second-order), one with moving modulations of luminance (first-order).

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